Preliminary determination of wood stocks for evaluation of carbon storage in forest systems of landslide slopes

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Abstract. The main purpose of the study is to determine the dynamics of wood volumes in tree populations by forest communities of landslide elements for further assessment of carbon sequestration and to identify the possibility of population-based methods for indicating landslide activity. The studies were carried out in 2008-2019 at specially protected natural reservation "Massiv-Dachny" on the right bank slopes of the Volga River (Tatarstan, Russia). As a result of the research, it was revealed that a distinctive feature of slope forests under conditions of landslide-scree processes is a decrease in the proportion, forest stand and crown density of native forest-forming species – *Q. robur*, *P. sylvestris*, and an increase in the proportion of *A. platonoides*, *B. pendula*, *P. tremula* with lower depositing capacity. Under conditions of temporary stability of landslide elements, the formation of long-term derivative *T. cordata* forests occurs. Clear cuttings of old-growth primary oak forests with pine carried out in 2018-2019 rise the risks of new landslide displacements and led to imbalance in the composition and structure of slope phytocenoses. For the first time for the study area, a database of morphometric and population parameters of trees in phytocenoses of landslide slopes was formed.

1 Introduction

The population dynamics of forest-forming tree species on the right bank of the Volga River reflects the degree of forest disturbance or restoration, which is important for strengthening slopes and preserving natural vegetation under the influence of the Kuibyshev reservoir. The water level fluctuation in the Kuibyshev reservoir varies on average up to 6 m per year [1], which has a significant impact on the exogenous slope processes activation and the phytocenoses transformation along the banks of the Volga and the Kama rivers [2-3]. Various anthropogenic impacts – road construction, local fires, unauthorized clear, sanitary and selective felling on slope areas, exacerbate the intensification of erosion and landslide processes. Therefore, monitoring of slope forests state is relevant in terms of preventing new exogenous hazards activation. To prevent landslide activity, the coordinates of the hazardous area location, slope stability assessment, and new displacement inventory are important [4-6]. Application of modern instrumental

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methods – terrestrial laser scanning, unmanned aerial vehicles, global navigation satellite system, allow to study the history of landslide slopes transformation and to predict their further development [7-9].

The biofix-offset strategy for industrial emissions suggests that 15-60% of anthropogenic carbon emissions can be offset by reforestation or afforestation. Presumably, 92% of carbon sequestration occurs in forest ecosystems, about 7-8% is accumulated in other land and ocean systems [10]. The assessment of the carbon sequestration capacity of Russian forests is ambiguous, and according to some researchers, the carbon pool varies from 28 to 71 Gt [11]. To determine the depositing function of various types of trees, height indicators, tree stem diameter, crown branches and needles weight, as well as the wet and dried stem wood disks weight are used. About 45-70% of the phytomass is in the trees stem [12-13]. The carbon content of dry tree phytomass is determined using conversion factors that range from 0.45 to 0.53. For the northeast of the European part of Russia, the net primary production (NPP) of carbon in pine phytocenoses varies within 1.9-4.5 t C ha^{-1} yr^{-1}. It was revealed that the forest stand takes 32-73% of the total net production [12, 14]. Carbon NPP is calculated using various methods [15]. The exact wood stock and annual carbon sequestration in forested areas can be calculated from experimental studies on sample plots of natural and artificial plantations, and by extrapolating them to the territory of the study region [16-17].

However, the assessment of the carbon sequestration capacity of forest plantations, as a rule, is carried out on flat areas of watershed plateaus, less often during reforestation of technogenic sites [18]. There are practically no data on the assessment of wood stocks of slope forests along the banks of large rivers, which is often due to their disturbance and small areas. On the territory of Tatarstan, located in the basin of two large Volga and Kama Rivers and the Kuibyshev reservoir, largest in Europe, slope forests occupy significant areas. Along with the protection of riverbanks under landslide and scree processes, forests also carry out significant carbon sequestration. As a result, the primary task for assessments of carbon sequestration by slope forests is the databases on wood stocks formation, taking into account the morphometric parameters of trees in various environmental conditions. Plant communities can actively respond to environmental changes, therefore, they are excellent indicators of landslide processes, which often cause the death of forest ecosystems. They can be both individual organisms and their combinations (phytocenoses or populations of species), the presence of which indicates certain properties of the environment [19-21]. Spatial data about trees from reference undisturbed plots, as well as about disturbed trees on landslide slopes, is important for comparative dendrogeomorphological analysis [19, 22-23]. Along with plants, fungi are also used to indicate the state of the environment. In particular, they are able to accumulate various metals and indicate their presence in soil, water and atmosphere [24-25]. Macroscopic fungi respond to changes in soil parameters: accumulation or destruction of humus and litter, moisture or temperature, as well as the frequency or duration of precipitation and other abiotic parameters [26-27]. In addition, fungi can be indicators of old-growth forests and undisturbed communities [28].

2 Materials and methods

The main purpose of the study was to collect information to assess the carbon sequestration capacity of slope forests along the banks of large rivers and reservoirs. The following tasks were solved to achieve the research goal: to form trees morphometric parameters database; to determine the wood volumes dynamics in tree populations of forest communities of landslide elements for further assessment of carbon sequestration; to identify the possibilities of population methods for indicating landslide activity.

Our work presents the use of primary data to assess the state of forest-forming tree species. The collection of field materials was carried out in the Verkhneuslonsky district of the Republic of Tatarstan (Russia) on the territory of the specially protected natural reservation (SPNR) "Massiv-Dachny", where, along with two biological stations of the Kazan Federal University, summer cottages are located (Figure1).

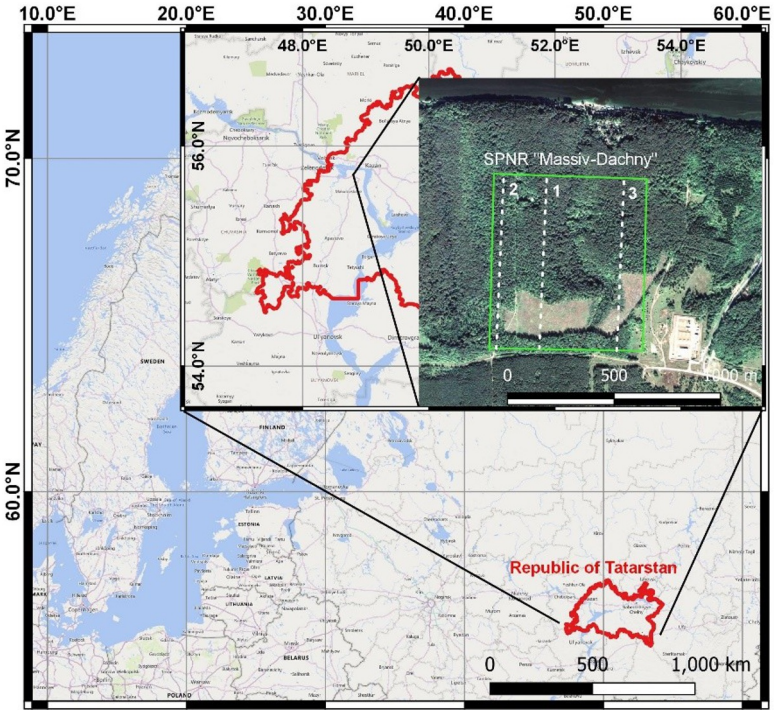

Fig. 1. Location of the study area. White dotted lines – geobotanical profiles. *Source*: Compiled by authors.

The territory belongs to the Volga high-plain region of broad-leaved forests. In 2014, there was a local fire on the territory of the "Ecolog" biological station and it was mothballed. On the territory of the biological station (the 1st stage of the landslide and the intra-landslide slope), the meadows were partially mowed, and the undergrowth under the woody vegetation was cut down. In recent years, intensive reforestation, and the secondary birch forests derivatives formation have been noted.

SPNR "Massiv Dachny" has the status of a natural monument of regional significance, created in 1989 and belongs to compartments 11 and 12 of the Sviyazhsky forest division [29]. The study area is limited by two deep ravines. Upper Quaternary and modern landslides are developed in this area. Some modern landslides are classified as old and stable, while others are active. Upper Quaternary landslides are medium-sized blocks, 30 m thick, consisting of crushed clays and marls with limestone interlayers. In the relief they form well-defined landslide steps. In separate areas modern landslides and ravines are developing in the body of ancient landslides, in the zone of groundwater wedging out and on landslide slopes. The causes of modern exogenous processes are the moistening of clay-marl rocks by underground, rain and melt waters, as well as the Kuibyshev reservoir high level [30].

As part of field studies, geomorphological elements of a landslide were identified on the landslide slope: the original slope, the crown of the landslide slope, the main scarp, landslide stages and minor scarps. In 2008-2012, studies of phytocenoses and populations

of forest-forming tree species were started to assess slope stability, and the forest community's state. In 2018-2019, clear cutting of old-growth coniferous-broad-leaved forest was carried out on the original section of the slope (Figure 2). As a result, the study of forest phytocenoses was resumed.

Fig. 2. Forest clear cutting at study area. Maxar Technologies Images ©. *Source*: Compiled by authors.

Three geobotanical profiles were organized on the slope (Figure 1). Within each element within the accounting area of 400 m², geobotanical descriptions of phytocenoses were carried out. To analyze the state of forest-forming species populations, all trees, considering ontogenetic groups, were mapped on graph paper. To assess the wood reserves, the height and diameter of the stem were determined at the level of 1.3 m for young, mature and old generative trees. Based on the height of the stem, as a sign of competitiveness for light, and the volume of wood, the functional characteristics of different tree species were determined by landslide elements. The dynamics of wood volume by landslide elements reflects not only the productivity of trees, but also the ability of different species to deposit carbon in the spatio-temporal aspect. The volume of wood was determined by the Guber formula (1) [31]:

$$V = G \times L \quad (1)$$

Where G – cross-sectional area at the length middle, m^2; L – the stem length, m.

Based on the assessment of the ontogenetic groups number the age structure and age range of forest-forming tree species populations were determined. According to the results of the trees age structure dynamics by landslide elements, the completeness of the tree population and their condition were determined. For further dendrogeomorphological analysis, core samples of *Pinus sylvestris* L. stems in forest phytocenoses were taken. All samples were taken according to standard procedures [32-33]. In this article, the obtained data were used only to determine the trees age.

Additionally, the species composition of basidial macromycetes was determined. These include fungi of Basidiomycota division, which have large mycothallus. In general, the fungi species diversity in Tatarstan has been most actively studied only in the last decade [34-36]. Based on estimates of the litter and humus saprotrophs and parasitic species number, it is possible to assess the fungal biodiversity dynamics under conditions of landslide processes and compare it with the original slopes. The studies were carried out by the standard traverse method. The material, easily identified in the field, was recorded according to the results of observations in a field diary. For other species, fruiting bodies were collected, dried, and identified. Information about the location, type of community and substrate was also indicated.

3 Results

Nominally primary old-growth oak forests with pine and linden grow on the original slope. The main forest-forming tree species *Quercus robur* L., *Tilia cordata* Mill., *Pinus sylvestris*

L. Long-term derivative lime forests with maple formed on the landslide body. In more humid areas, there are secondary derivative forests of *Populus tremula* L. are observed; in dry areas – forests of *Betula pendula* Roth. On the landslide crown, the main scarp, the 1st and 2nd stages, the proportion of *T. cordata*, *Acer platonoides* L., *Ulmus glabra* Hubs. increases, while the number of *Q. robur* and *P. sylvestris* decreases. In ravine-gully systems *T. cordata* is noted and the proportion of *P. tremula* and *U. glabra* rise with an increase in humidity or groundwater discharge. Both in the forest phytocenoses of the original slope and in the phytocenoses of landslide elements, the part of forest plants is 80-83%, which is due to reforestation processes and characterizes the landslide area of the SPNR "Massiv Dachny" as conditionally stable.

The stand formulas for the forest communities of landslide elements for 2011-2012 and 2019-2021 after clear cutting of the primary forest are presented in the Table 1.

Table 1. Characteristics of forest phytocenoses of landslide elements for 2011-2021.

Landslide element/profile	Stand Formula Profile 1		Stand Formula Profile 2		Stand Formula Profile 3	
	2011	2021	2011	2021	2012	2020
Original slope	4Q3P3T + A	–	4Q2P4T +A	–	3Q3P4T	–
Crown	4T3Q3P+A	5T2Q3P+A	3Q2P4T1A	2Q2P4T2A	4P4T2Q	4P4T1Q1A
Main scarp	5T3Q2P+A	5T2Q2P1A	6Pt2T2A+Q	5Pt3T2A+U	5T2Q3P	5T2Q3P
1st stage	5T2Q2P1A	4T1Q1P3A+U	2Q4P3T1A	2Q4P3T1A	6T2P2A	5T3P2A+U
2nd stage	6T2Q2B+A+U	6T1Q2B1A	6T2Q2A+U	6T2Q2A+U	8T2Q+A+P	8T1Q1A+P

Note: Q – Q. robur, P – P. sylvestris, T – T. cordata, A – A. platonoides, U – U. glabra, B –B. pendula, Pt – P. tremula. Source: Compiled by authors.

On the remaining edge of the original slope forest, where sanitary felling of trees was partially carried out, a new discount area was organized in 2021 to estimate the number of remaining trees. Features of the trees number dynamics with the obligatory consideration of the undergrowth (juvenile, immature, virginal individuals) population at landslide slopes phytocenoses are presented on the example of tree populations at 1st profile (Figure 3).

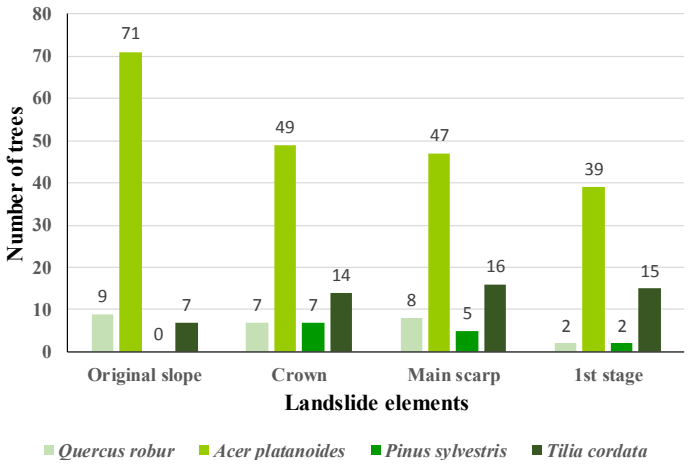

Fig. 3. Dynamics of the forest-forming trees number in landslide elements phytocenoses in 2021. *Source:* Compiled by authors.

Based on the results of the population analysis, it was revealed that the complete trees age structure is observed only for *T. cordata* and *A. platonoides* in almost all forests of the landslide slope (Figure 4). On the contrary, the *Q. robur* age structure is complete only for the remaining fragments of oak forests at original slope. Here, along with generative oaks, juvenile, immature, and virginal plants are observed sporadically; further along the slope,

oak is represented only by generative groups. The age structure of the *P. sylvestris* population is incomplete; it is represented only by large and rather old reproductive pines, since the undergrowth of light-demanding pine cannot be renewed under conditions of strong shading of the broad-leaved forest. Undergrowth is noted only in broad-leaved tree populations. Intensive undergrowth in the *A. platonoides* populations is seed origin, while in *T. cordata* populations it is predominantly vegetative and less often seed origin.

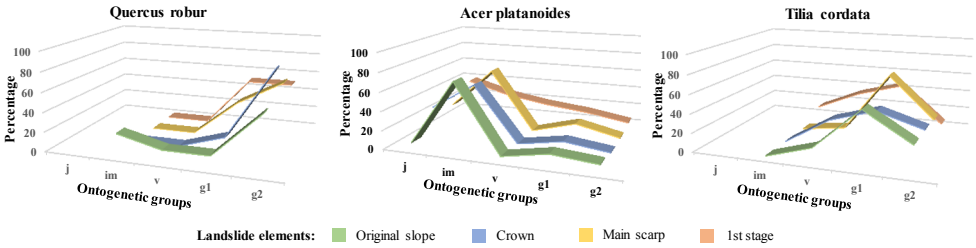

Fig. 4. Age spectra of *Q. robur*, *A. platonoides* and *T. cordata* populations at profile 1: **j** – juvenile, **im** – immature, **v** – virginile, **g1, g2** – generative of 1st and 2nd order. *Source*: Compiled by authors.

For a preliminary assessment of carbon sequestration in the forest communities of landslide slopes, the definition of wood stocks was used, which was considered as the sum of the wood volumes for each type of tree in terms of 100 m^2. Comparing the results of the wood volumes dynamics in 2011-2012 by landslide elements, it was noted that in long-term derived lime forests of landslide crown, main scarp and the 2nd stage, the wood volumes indicators of *T. cordata* correspond to those wood characteristics in conditionally native oak forests of the original slope – 16-24 m^3 (Figure 5 a). However, the wood volumes of *Q. robur* and *P. sylvestris* in landslide elements phytocenoses reduced by 1.5-2 times.

After clear cutting of old growth oak forests, the wood volumes of *Q. robur*, *T. cordata*, and *P. sylvestris* and, accordingly, carbon sequestration in the forests of the original slope decreased significantly. As an example, we present the dynamics of wood volumes of different types of trees for 2012 and 2021 in forest phytocenoses of the 1st profile (Figure 5).

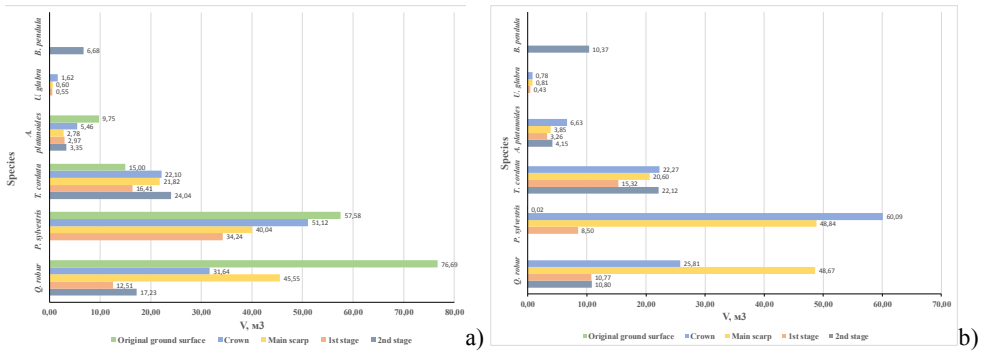

Fig. 5. Dynamics of *Q. robur*, *P. sylvestris*, *T. cordata*, *A. platonoides*, *U. glabra*, *B. pendula* wood volumes by landslide elements before (a) and after (b) clear cutting of the primary slope forest. *Source*: Compiled by authors.

Dendrological analysis of *P. sylvestris* stems was used to determine the trees age. On the original slope and landslide crown *P. sylvestris* is 120-140 years old; these are mature reproductive trees (Figure 6).

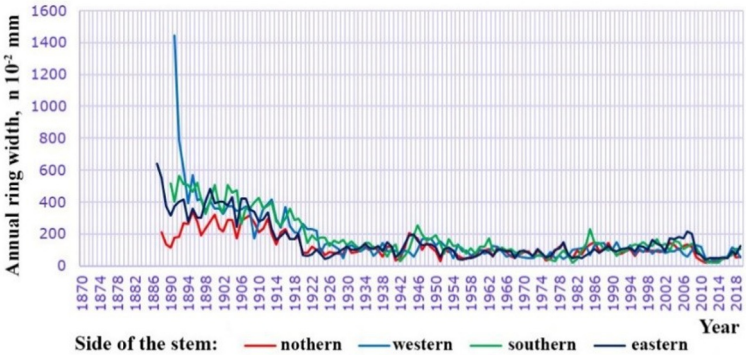

Fig. 6. Dendrograms of *Pinus sylvestris* on original slope/crown. *Source*: Compiled by authors.

Clear cutting in 2018 on the primary slope of the SPNR "Massiv-Dachny" led to the activation of erosion processes. The study of basidiomycetes in the ravine-gully system communities revealed the litter disturbance. As a result, on the slopes of the ravine, especially in its upper reaches, an increase in the proportion of humus saprotrophs and mycorrhiza-forming organisms is noted. These are fungi that inhabit the humus horizon, in particular, representatives of the *Boletaceae* family: *Boletus reticulatus* (Hoffm.) Pers., *Neoboletus* spp., *Hemileccinum impolitum* (Fr.) Šutara, *Xerocomus subtomentosus* (L.) Quél. and etc. The vast majority of them form mycorrhiza with broad-leaved tree species. In addition to them, there are also other humus saprotrophs and mycorrhiza-forming organisms belonging to the *Inocybaceae*, *Amanitaceae*, *Russulaceae*, *Cortinariaceae* families. However, the proportion of litter saprotrophic fungi has sharply decreased due to the disturbance of substrates because of landslide and erosion processes activation.

Population database of slope forest trees, created in 2008, is a set of combined blocks: "PLOTS" – contains discount area coordinates, landslide element and phytocenosis types, stand formula and type of impacts; "PLANTS" – contains phytocenosis plant species lists with number assessment; "SPECIES" – contains each tree species coordinates by ontogenetic groups and their morphometric parameters (height, stem diameter in meters); "AGE_CODES" – reference book about ontogenetic groups of trees; "ECG" –contains the ecological-coenotic groups names of plant species; "INVESTIGATIONS" – contains the identification code of the key population specification on the discount area [37].

4 Discussion

The wood volumes of forest-forming trees, as well as their cross-sectional areas, reflect the productivity of forest communities and the phytocenoses reforestation stages by landslide elements [2, 11, 18]. Phytocenoses and tree population's study of the landslide elements by three profiles at SPNR "Massiv-Dachny" in 2011-2012, indicate the landslide processes decrease. This is due to reforestation and the long-term derivative lime forests formation, which contributed to the substrate fixation and the landslide slope stability. Forest-forming tree species state and their populations structure often used as indicators of the landslide slopes activity/stability [19-20, 22-23, 33].

Ufimtsev V.I. and Androkhanov V.A. (2022) noted that after anthropogenic impacts in disturbed forests the composition and structure of tree populations change, and both wood stock and carbon sequestration in general often decrease [18]. After clear felling of the primary slope forest in 2021-2022, the loss of *Q. robur* wood volumes decreased. In 2012, the volumes were 76.7 m^3, the average tree height was 24-25 m, the average diameter – 0.68 m. In modern conditions, the volumes of *Q. robur* wood are zero. In 2019, young *P.*

Sylvestris were planted in place of an old-growth oak forest. In 2022, the average number was 31 individuals per 100 m^2, part of the undergrowth, apparently, dried up. The average young pines wood volume is 0.02 m^3. In 2012, the sum of *P. sylvestris* wood volumes was 58 m^3 per 100 m^2, the average tree height was 26-28 m, and the average stem diameter was 0.61 m. The sum of the wood volumes of *T. cordata* on the primary slope in 2012 was 15.2 m^3, the average stem height of reproductive specimens – 17.5 m, the average diameter – 0.33 m, the sum of *A. platonoides* wood volumes on the original slope – 10 m^3, the average stem height – 16 m, and the average diameter – 0.26 m. Thus, in 2012, the sum of wood volumes of the 1st and 2nd forest layers was 162 m^3 per 100 m^2 (Figure 5).

After clear cutting, wood loss per 1 ha of forest was 16200 m^3. It will take at least 30-50 years to restore a forest that can store carbon. As noted by a number of authors, the greatest accumulation of carbon in the dry tree phytomass is observed mainly in the stem wood [11-12]. That indicates the necessity of an accurate determination of the stem wood stocks on test sites both in natural and disturbed forests [16-17, 29].

Numerous scientific studies demonstrate the successful use of fungi as bioindicators for forest communities monitoring [25-26, 28, 35]. According to different types of fungi identification results, litter saprotrophs on slope areas are localized only in small "pockets" where the litter remains due to the features of the microrelief. The main share of xylotrophic species is concentrated at the bottom of the ravine, where dead wood accumulates. This distribution of fungi does not correspond to the usual for forest communities in flat areas and creates a certain imbalance in the ratio of ecological groups. In places of strong erosion, where soil collapses are observed, for obvious reasons, even humus saprotrophs and mycorrhiza-forming organisms are not observed. Further observations will make it possible to establish the fungal community dynamics and predict the clear cutting consequences. It should be noted that the studied forest community is a habitat for fungi rare species included in the Red Book of the Republic of Tatarstan.

5 Conclusion

The paper is devoted to the assessment of forest-forming tree species state, which, based on various correction factors, will allow estimating the carbon sequestration dynamics by different tree species under landslide slopes conditions. A distinctive feature of slope forests under conditions of landslide-scree processes was revealed as a result of the conducted research – decrease in the proportion of native forest-forming tree species (*Q. robur* and *P. sylvestris* in our study), their stand and crown density, and timber reserves. On the contrary, the proportion of fast-growing species with a lower depositing capacity – *A. platonoides*, *B. pendula*, *P. tremula*, increases. Long-term derivative *T. cordata* forests appear only under the landslide elements stability condition. However, in terms of wood reserves, they are inferior to conditionally indigenous communities.

As part of the research, a unique database of trees morphometric and population indicators for forested landslide slopes was created. Based on the measurements data collected in 2019-2022 period, it is possible to assess the dynamics of trees number and wood stocks and to identify the impact of clear cutting or sanitary felling on the further state of forest-forming tree populations under conditions of landslide and erosion processes in the forests of the Kuibyshev reservoir banks. The results of the study confirm the possibility of applying of methods for analyzing of forest-forming tree populations dynamics to determine landslides and other dangerous exogenous processes activation.

Continuation of the started monitoring studies, collection of information for the database, determination of trees morphometric parameters, opens up prospects not only for wood stock calculation, but also, when applying correction factors, makes it possible to

determine the carbon sequestration of different tree species, which is an important part of the carbon balance of slope forests.

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